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AN ENGINEERING EVALUATION OF RESIDUAL
STRESS EFFECTS

(OSRD REPORTS 3348, 3580, 4396)

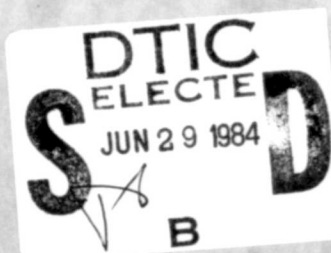
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By: R. Palme, H. Udin and J. Wulff
M.I.T. -- September 20, 1954

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Special Literature Evaluation Report

September 20, 1954

AN ENGINEERING EVALUATION OF RESIDUAL STRESS EFFECTS

(OSRD REPORTS 3348, 3580, 4396)

by

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I. Summary

This report consists of an engineering evaluation of OSRD Reports 3348,¹ 3580,² and 4396.³ An introduction containing an orienting discussion of the general problem of residual stresses and their effects on the mechanical behavior of weldments is followed by detailed summaries of the above three reports. The results and conclusions contained in the reports are discussed and evaluated in the light of the present literature.

The following conclusions are reached in this evaluation:

(1) Concerning the effect of residual stress on ballistic performance, the most significant point in this (and other) reports is that appreciable plastic deformation of a weldment obliterates any locked-in stress system. Fracture of ballistically loaded welded armor in the field is nearly always accompanied by extensive plastic deformation. Therefore, if it can be shown by field tests that deformation precedes fracture, the question of effect of locked-in stress becomes relatively unimportant.

(2) The subject reports do not give clear-cut answers as to the effect of residual stress on performance; nor will these answers be found in the literature. The reason is straightforward. To investigate the effect of a

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1. Weldability of Commercial Armor Plate: A Preliminary Investigation of Residual Stress in Welded H-Plate, by R. H. H. Pierce, Jr., and W. G. Benz.
OSRD Report No. 3348, February, 1944
 2. Effect of Locked-Up Stresses on Ballistic Performance of Welded Armor - Part I, by D. Rosenthal, J. R. Clark, S. B. Maloof, and John T. Norton.
OSRD Report No. 3580, April 18, 1944.
 3. Effect of Locked-Up Stresses on the Ballistic Performance of Welded Armor - Part II, by John T. Norton, D. Rosenthal, and S. B. Maloof.
OSRD Report No. 4396, November 24, 1944.



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parameter (residual stress in this instance) means must be found to vary this parameter while holding everything else of unknown effect constant. Nobody has yet succeeded in doing this because (a) residual stress of yield-point magnitude is always attained in a weldment of significant size; (b) variation of this stress level by post-weld thermal treatments introduces metallurgical variables of indeterminate magnitude; (c) variation of the residual stress level by post-weld straining induces strain-aging and age-hardening factors of unknown effect.

(3) The metallurgical effects of post-weld thermal treatments appear to outweigh the effect of these treatments on residual stress levels.

(4) If research on the effect of residual stress on ballistic performance is to be continued, it is strongly recommended that specimen geometry, test temperature, and loading rates be devised such that failures involving no plastic deformation are induced. While such tests may have no obvious practical application, it is felt that no other conditions of test can lead to significant answers.

(5) From the practical standpoint of building armored equipment, consideration should be given to changing process schedules so that facilities now devoted to or intended for stress-relieving the final weldment can be used for intermediate stress relief of the partly welded units. There is ample evidence that intermediate stress relief lessens cracking during welding,¹ and no clear-cut evidence that post-weld stress relief improves weldment performance.

1. "The Welding of Heavy Sections," by W. Spraragen and M. A. Cordovi, Welding Research Supplement-369 S - 386 - S. August, 1954.

II. Introduction:

In published literature surveys (1)¹ and lists of fundamental research problems (2), emphasis is placed on the need for basic data on residual weld stresses. Due to the lack of such data the major questions in this field are to a large extent unresolved. The importance of these questions becomes obvious when it is realized that they are intimately related to the problem of weldability, which, in turn involves the joinability and performance of weldments. Considered in all their aspects, no more practical and economically important problems than these exist for the welding engineer.

Joinability is defined as the degree of soundness of a metal after being subjected to a given welding procedure, and the degree of soundness depends upon the presence or absence of defects, which may be of four types: weld metal cracks, base metal cracks, weld metal porosity, and weld metal inclusions(3). Joinability is thus an indication of what has happened during the welding operation. Joinability is usually² established (although not necessarily known until the proper inspection of the weldment has been made), once the welding operation (including subsequent heat treatment, if any) is over, and the weldment has returned to ambient temperature throughout.

The other aspect of weldability, the performance of a weld or weldment, is defined in terms of its mechanical behavior after welding is completed, relative to the mechanical behavior of its prime plate before welding (3). Thus, while joinability is almost exclusively of interest to the welder and welding engineer, performance concerns the design engineer, the testing

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1. Numbers in parentheses refer to the bibliography at the end of this report.
 2. This implication of a case where it may not be will be made clear in the subsequent discussion of aging phenomena.

engineer, and the user, as well.

The above definitions seem distinct and separate, but before going on, it should be pointed out that where aging phenomena occur after welding, there is a possibility of some confusion arising. In certain cases, aging phenomena which cause a loss of local ductility in a weld after welding is completed may result in the formation of weld or base metal cracks. These may not occur until considerable time has elapsed after welding, but, nevertheless, they will be due to phenomena arising during welding. Thus it would seem that such cracks should be considered as an indication of joinability, but the situation is not so clear-cut if the cracks due to aging do not occur until the weldment has been placed in service or subjected to performance tests, and failure is caused by, or aided by, their presence. The reason for bringing up this point in detail here will be brought out in the subsequent discussion of residual stresses and weldability.

The interest in acquiring basic data on residual weld stresses arises from the fact that there is no satisfactory answer to the question: to what extent and in what manner do residual weld stresses affect weldability? In view of the definition of weldability discussed above, in terms of joinability and performance, it can be seen that this question can best be considered in terms of its implications for each of these two separate aspects of the main topic.

Considering first joinability, the only way in which this can be affected by stresses is through their effect on the formation of base or weld metal cracks, since these are the only two defects included under soundness, or joinability, which may be stress-induced. In fact, stresses must be present for them to form¹. In the absence of external loading, here excluded by definition because

1. A crack can only form at any temperature in the presence of stress, for its formation results in the generation of new surfaces. The energy associated

we are not considering performance, the only stresses which can be present in any weld or weldment during and until the completion of welding, are residual stresses². Thus, it follows, that, although one or several of a number of possible causes³ may be responsible for their presence, and their effectiveness may be enhanced by one or more of still other factors⁴ which weaken a weldment toward their action, residual stresses⁵ alone are the only ultimate cause of base and weld metal cracks formed during welding. However, the manner in which they act and the extent to which they act to cause these cracks, together with the influence of the many variables, are not known, and only elaborate experiments can determine them.

From this it is clear that the proper evaluation of the role of residual stresses in joinability requires the detailed measurement (preferably throughout a weldment) of such stresses as they are formed; that is, as a function of time during the welding operation, until the weldment reaches ambient temperature (and longer if aging effects must be included). The stress distributions so determined must be correlated with the initiation and propagation of whatever

with these surfaces (surface energy) can only be supplied from the elastic energy stored in the vicinity of the crack before its formation; this stored elastic energy (in terms of an energy density) is the stress at this location.

2. Here considered to be the resultant stress at any point in the weldment at any moment during welding. Thus it may properly be called a "dynamic residual stress" as opposed to the final usually-considered resultant "static residual stress" present at the end of the operation. The term resultant stress here includes any reaction (or restraint) stress as a component.

3. Thermal strains, phase transformations, etc.

4. Stress concentrations (including notches, porosity, and inclusions), segregation, etc.

5. That these may or may not have reaction components, or that micro-stress effects may cause the cracks does not affect the argument.

weld and/or base metal cracks form, if any, taking into account, of course, the time and temperature at which they appear.¹ Only in this way can the influence of the many variables be determined and the possibilities for controlling and improving the joinability of weldments assessed.

In view of the obvious experimental difficulties involved in such a program as described above, it is not surprising to find that practically no data exists for this aspect of the residual weld stress problem. So far as can be determined only one investigation in this field has been made. Winterton and Wheeler (4) measured the transverse reaction stresses considerably removed from the weld during and after the butt welding of laterally-constrained mild and alloy steel plates. The severe constraint imposed resulted in complete failure at the weld when cracking occurred, and the only correlation obtained between the stress-time curves and cracking was the obvious complete drop off in the curves at failure. A slight dip in the curves was considered to correspond to the martensite transformation in the weld zone. The transverse restraint stresses recorded were smaller than expected for the fractures which occurred.

A valuable contribution should be made to the joinability weld stress problem by the research program in progress at M. I. T., for its purpose in part is to determine the effect of restraint on the formation and variation of residual stresses during the welding of a high-tensile steel. These measurements will be correlated with crack formation wherever possible.

The other great need for information regarding the effect of residual stresses is in the mechanical behavior or performance aspect of weldability(2).

1. Thus this problem is similar to the one discussed below, under the role of residual stresses in weld performance, where a correlation of stresses with brittle fracture is required. Here, however, the fundamentals of the formation of cracks at high temperature (hot tearing) must undoubtedly also be considered.

in spite of the considerable number of researches which have been conducted in this field.¹(1,5,6,7)

The problem may conveniently be divided into two categories. Namely, what effect do residual weld stresses have upon the behavior of weldments under conditions of:

1. Static (or slow) and rapid loading where fracture is preceded by considerable plastic deformation?
2. Static (or slow) and rapid loading where fracture is preceded by little or no plastic deformation?

It is only in the first category that any definite answers seem to be available regarding the effect of residual weld stresses, but this is in some respects a relatively trivial and economically unimportant case, most weld failures occurring under the conditions of the second category. The former includes, primarily, situations of service overstressing, and the remedy is usually evident. Even so, misconceptions still exist concerning it; in fact, in some aspects it is not fully understood.

The presence of a residual stress changes the effective proportional limit of a weldment during slow loading (8,9,10), beneficially, if the external load results in stresses which are locally of opposite sign to the existing residual stresses, and vice versa. It has been argued forcefully, but not very logically (11) that this is not so, it being maintained that the load-deformation curve for a structure containing residual stresses is essentially the same as for one without such stresses. Whatever truth is contained in such a statement may be attributed to the fact that large overall factors of safety (based on the proportional limit) are used in most welded structures

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1. The majority of residual weld stress researches (1) have reported data on the measurement of the stresses which exist in completed weldments, but none on their effect on subsequent performance.

and that the onset of plastic deformation tends to reduce or at least obscure the residual stress effect. Locally, however, such residual stress effects can be considerable¹.

Before going further, it is relevant to point out the difference between so-called ductile and brittle fractures in metal. Both are initiated upon the occurrence of a crack in the metal, and, as stated in a footnote earlier in this introduction, the presence of an elastic stress field in the surrounding region is necessary for such an occurrence. The difference, however, between a ductile and a brittle fracture, lies in the manner in which the initiating crack is propagated (13). A brittle fracture crack is propagated by the continued "release" of the elastic stress field surrounding it, whereas, a ductile fracture crack requires plastic deformation work to extend it. The surrounding elastic stress energy is generally insufficient to provide the latter, so such a ductile fracture crack can propagate only if work is continually done by the external forces.

Continuing with the discussion on the effect of residual weld stresses, there seems to be general agreement (5,6,7, 8) that if appreciable plastic deformation takes place beyond the proportional limit during slow loading, any residual weld stresses initially present in a structure will have no effect upon its ultimate failure, whether this failure be evidenced by ductile or brittle² fracture. That is to say, residual stresses have no effect upon

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1. The position has been restated recently by Yang and associates (12) in reference to a welded steel beam: "the factor of safety has always included the reduction of load carrying capacity due to residual stresses, but the percentage reduction due to (these stresses) has not generally been appreciated."
 2. Orowan (13) has pointed out that it is possible for brittle fracture to occur following appreciable plastic deformation.

the fracturing of metals when such fracturing is preceded by considerable plastic deformation. This is so because the plastic deformation obliterates the initial residual stresses.¹

The situation is not nearly so clear cut for the economically more important case of brittle failure, which has been the subject of so much discussion and investigation (1a, 13, 14), because it is so significant to technology and because it has thus far largely defied understanding.

The lack of understanding of brittle fracture does not arise from any dearth of observational data regarding its occurrence, but rather from the apparent inability to perform the definitive experiments necessary to determine the basic causes of crack initiation and propagation, especially the former. Indeed, it is not certain what these experiments should be, although a number of approaches are suggested (1a, 2a), unfortunately in rather general terms. The difficulties are increased by the number of variables which enter the problem (13, 14).

Thus, for other than conditions of slow loading accompanied by plastic deformation, the problem of the effect of residual stresses on the performance of weldments becomes one of determining their effect on the initiation and propagation² of brittle fracture cracks. To the complications discussed above are thus added the metallurgical and structural variables inherent in welding (13), together with large specimens and complexity of analysis (2a), and the approximate nature of the results which currently characterize residual weld stress measurements, especially when triaxial stress distributions³ are investigated.

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1. Although recently-presented arguments (1a) suggest that this is probably not so on a micro-stress scale.
 2. The local values of residual stress and their short-range variation are probably of greatest importance to the initiation of brittle cracks, while the values at a distance, or possibly only the reaction components, may be important for crack propagation (2a).
 3. Since it is recognized that brittle fracture is an indication of the presence of local triaxial stresses (13), fine-scale three-dimensional residual stress measurements are necessary for a proper study of the problem.

III. Summaries of Reports to be Evaluated.¹

A. OSRD Report No. 3348: a Preliminary Investigation of Residual Stress in a Welded H-Plate.

1. Experimental Program:

In order to "assist in interpreting the results of ballistic tests" of standard welded H-plates (36 inches by 36 inches by 1-1/2 inch, over-all) of armor composition,² the residual stress distribution in one such plate in the as-welded condition (NR-27) was determined in some detail by a method of sectioning the plate by saw cuts in the weld metal parallel to and immediately outside the heat-affected zone, and away from the welds; a disc was also trepanned from the plate. The relief of residual surface strain resulting from these cuts was measured by several different types of strain gages of various sensitivities, including SR-4 resistance gages and caliper gages, all of which agreed within their respective accuracies whenever their results were compared.

Prior to this principal investigation two other tests were made. First, an H-plate (NR-17) already fractured adjacent to one leg of the H-weld in a ballistic shock test, was sectioned by a series of parallel saw cuts adjacent to and along what remained of the cross-bar of the H-weld. Residual strain relief on the surface of the cut-away strips was measured by caliper gage. Second, each of two H-plates, as welded plate NR-27, to be used in the main investigation, and one similar to it except for an added "armor" heat treatment, NR-28, were supported near their corners, centrally loaded, and the surface strains at various locations in the weld metal, both parallel and transverse to the legs and cross-bar, measured by SR-4 gages as a function of the centrally-applied load. "Stresscoat" lacquer was also used to detect strains

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1. For further details than are presented here, the reader is referred to the original OSRD reports.
 2. A short tabulation of pertinent data, such as prime plate compositions, electrodes, and heat treatments used, etc., is included at the end of each experimental program summary.

in the latter tests. In each case the load was applied in 10,000 lb. increments up to 120,000 lb., then similarly removed, following which a second load cycle in 20,000 lb. increments was made.

Table I - Welded H-Plate Data

Analysis:

<u>Plate</u>	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>Zr</u>
NR-17	0.26	0.84	0.021	0.019	0.24	1.01	0.72	0.53	-	-
NR-27, NR-28	0.30	0.93	0.026	0.025	0.71	-	0.70	0.20	-	0.09
Weld Metal	0.12	0.54	-	-	0.21	1.72	0.38	0.77	0.12	-

Electrode: SW-101 Ferritic Preheating Temperature: 350°-400°F

Plate NR-28 Armor Heat Treatment After Welding:

3 hours at 1650°F, air cooled.

2 hours at 1650°F, water quenched.

3 hours at 1230°F, air cooled.

H-Welds made by first welding the two legs in succession, then welding the cross-bar. The final weld beads were then ground flush on both sides of the plates.

Plate NR-17 made with single-V joints throughout.

Plates NR-27 and NR-28 made with double-V joints throughout.

Proportional limit of weld metal = 83,000 psi.

2. Results:

The saw-cutting of the ballistically-fractured H-Plate (NR-17) indicated an average release of tensile stress in the crossbar weld metal of 32,500 psi, in the heat-affected zone of 25,000 psi, and in the adjacent plate metal of 5000 psi.

During the loading of the "armor" heat treated H-Plate (NR-28) in transverse bending the induced strain remained proportional to the applied load throughout the range during both load cycles. Since the stress corresponding to the maximum strain measured was of the order of 53,000 psi, any residual tensile stress in the weld metal must have been less than approximately 30,000 psi, the difference between the yield point of the weld metal (83,000 psi) and the maximum applied stress, in view of the fact that no yielding took place. Definite breaks (sudden changes of slope) in some of the plots of load vs. induced strain for the first-cycle loading of the as-welded H-Plate (NR-27) indicated the beginning of plastic yielding for an induced stress as low as 22,500 psi. Thus, by the above reasoning, a residual stress of at least 60,500 psi must have been present at the particular location, the junction of the leg and crossbar welds in the direction of the leg weld. In this way a transverse stress in the crossbar weld of 50,000 psi was indicated. Upon the first unloading the load-strain plots were straight lines with no breaks, showing that certain of the residual stresses had been reduced. The second-cycle loading and unloading then followed the straight lines corresponding to the first unloading, confirming this.

The cutting of the as-welded H-Plate (NR-27) by a series of saw cuts and a trepanning resulted in the measurement of a maximum longitudinal residual tensile stress along one leg of the weld of 72,000 psi and along the crossbar of the weld of 15,000 psi. The drop-off in stress from the welds to the heat affected zone and adjacent plate was marked. Transverse tensile stresses

existed along the weld crossbar and the portion of the weld leg halfway between the edge of the plate and the crossbar.

3. Conclusions:

a) There is a high longitudinal residual stress along the weld in a H-Plate, the maximum value found being of the same order of magnitude as the proportional limit of the weld metal. A steep stress gradient exists through the heat-affected zone into the plate metal. Definite indications existed for considerable transverse weld stresses. Stresses within the weld perpendicular to the plate surface probably also exist.

b) The "armor" type of post-weld heat treatment acts to relieve the residual stresses appreciably.

c) Since the as-welded H-Plate residual stress distribution is no doubt a function of the welding procedure, an improvement over the somewhat random method used for plate NR-27 is suggested for systematic investigation of such stresses when the welding procedure is varied; for example, by using a ferritic NRC-2A electrode in one case and a conventional austenitic electrode in another.

B. OSRD Report No. 3580: Effect of Locked Up Stresses on Ballistic Performance of Welded Armor - Part I

1. Experimental Program:

Transverse explosive loading was used on several series of armor plate specimens, supported as beams in simple bending, to simulate the shock loading of ballistic tests.

a) Prime Plate Tests:

To separate the effects of the welded joint from those due to residual stress, and to serve as a basis for the design of the welded test specimens, the first test series consisted of preliminary explosive loading experiments on unwelded prime plate. Several sets of specimens 3 inches wide

by 10 inches long were cut from armor heat-treated plate 1-inch thick; each set of at least five duplicate specimens was further treated as follows before testing:

- Set 1: Surface ground.
- Set 2: Surface ground and stress relieved.
- Set 3: Surface ground, stress relieved, and etched to remove residual grinding stresses.
- Set 4: Surface ground, stress relieved, and heated centrally in a resistance welder to induce a local residual stress pattern (softening occurred at and slightly below the surface where contact was made with the electrodes).
- Set 5: Surface ground and softened throughout to the minimum hardness found in the softened zone of set 4, by heating above the stress relief temperature used in sets 2, 3, and 4.

The residual stress pattern obtained in set 4 was found by X-ray measurement to be one of biaxial tension of about 85,000 psi in the center of each surface; like the softened region, the pattern was superficial and did not extend much beyond a depth of $1/8$ inch or radius of $1/2$ inch, dropping off rapidly from the center to these points. Using an approximate method developed by Norton and Rosenthal especially for this work, the variation with thickness of the residual stress in the direction of thickness was also determined for a thermally-stressed specimen like those in set 4. It was found to be a compression stress with a maximum value (at the midplane) of -7800 psi (± 5000 psi).

The specimens were supported at their ends as flat beams and a two-inch diameter charge of explosive detonated in the center of the top of each. Charges of differing weight were used for each specimen in a set. The first appearance of a surface crack was taken as the criterion of failure and charges above and below this value were used.

In order to determine the influence of the orientation of the explosion-produced crack on its propagation, two sets of 3-inch by 10-inch by 1-inch thick

specimens were cut from 4-inch thick blocks of prime plate in such a way that the "planes of weakness" (assumed parallel with the rolling plane) were parallel for one set, and perpendicular for the other, to the 3-inch by 10-inch surface, being oriented along the 3-inch width in both cases. These specimens were subjected to explosive loading as above and sectioned.

b) Welded Plate Tests:

Plates 22 inches long and 6 inches wide were cut from the prime armor plate and welded in pairs along the 22-inch edge using double-V butt welds, in most cases with a ferritic electrode while a few welds were made with an austenitic electrode. Three explosion tests specimens were cut from each plate, 3, 5, and 11 inches wide, the weld running along their centers in the width direction. The weld beads were not ground flat but left as welded.

The specimens were further heat treated and divided into sets for explosion as follows:

<u>Set</u>	<u>Weld</u>	<u>Treatment</u>
1	Austenitic SW-164	As welded
2	Ferritic SW-101	As welded
3	Ferritic SW-101	Armor treated
4	Ferritic SW-101	Stress relieved

The original plates for sets 1 and 2 were stress relieved before welding. At least three and often five specimens of each width (3,5,11 inches) were in each set.

The four sets of welded specimens were subjected to the same type of explosive loading tests as the prime plate specimens in (a). In addition to noting the charge at which a surface crack appeared, however, an attempt was made by sectioning the specimens to determine the smaller charge necessary to produce the first internal crack.

By a subdivision method using SR-4 strain gages on the plate surfaces, the residual stress patterns parallel and perpendicular to the axis of the weld

were measured for the middle portion of single 3, 5, and 11-inch wide specimens of ferritic as welded set 2, and for one 11-inch specimen of stress relieved set 4. In preparation for those gages which were mounted on the weld bead itself, the latter was given a flat portion by grinding, but not ground flush with the rest of the plate.

Table II - Test Plate Data

Analysis (of 1-inch thick prime plate):

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Mo</u>
0.26	1.65	0.016	0.018	0.19	0.48

(Note: no analysis given for 4-inch thick prime plate used in crack orientation tests.)

Electrodes: SW-101 Ferritic
SW-164 Austenitic

Welding Preheat: 350° - 400°F for ferritic welds; none for austenitic welds.

Interpass Temperature: 350° - 450°F for ferritic welds;
200°F max. for austenitic welds.

Heat Treatment and Resultant Hardness:

(a) Prime plate tests:

Armor heat treatment: 1-1/2 hours at 1625°F, spray quench and draw at 860°F for 3 hours, air cooled, BHN 352-363.

Stress relief heat treatment: 1/2 hour at 1135°F, air cooled, BHN 275

Softening heat treatment: 1 hour at 1250°F, air cooled, BHN 220

(b) Welded plate tests:

Armor and stress relief heat treatments same as above.

2. Results

a) Prime Plate Tests:

The overall bending effect of the explosive loading on the 3-inch by 10-inch by 1-inch specimens appeared similar to that caused by a local static load of 91,700 lbs.¹ The nature of the explosive loading failure was the same in all five sets of specimens. In order of increasing weights of charge: the top surface was indented; the specimen was bent as described above; failure began as an internal crack directly beneath the explosive block, generally parallel to the bottom face of the specimen and between 1/4 and 1/2 inch from the bottom; the internal crack opened wider, producing a blister on the bottom of the specimen; one end of this blister tore through to the bottom producing a surface crack; the entire blister tore away (back spall); and, finally, when the charge was large enough, the specimen broke in two.

The surface of the internal crack was granular, as in a brittle fracture, while the crack which propagated to the surface appeared smooth and silk-like. A grid on the surface of one of the specimens showed considerable plastic deformation adjacent to the surface crack.

The weights of charge necessary for the appearance of the surface crack for the different sets of specimens were (in grams, ± 10):

Set 1: 120	Set 4: 130
Set 2: 150	Set 5: 110
Set 3: 150	

The corresponding charges for the appearance of the internal cracks were not determined. Internal cracks were present in all specimens tested, down to the lowest charge of 100 grams (used for all 5 sets).

1. No internal cracks occurred during static loading, however.

Explosive loading of the orientation specimens produced internal cracks parallel to the oriented "planes of weakness," at about equal weights of charge for the two cases (100 grams). The crack perpendicular to the surface propagated to the surface with no appreciable increase in charge, while the parallel crack required 30% more charge to reach the surface.

b) Welded Plate Tests:

The nature of the explosive test failures was much the same in all four sets of specimens. It was similar to that found in the prime plate tests in some particulars, but differed in others. The indentation and bending were quite small, probably due to the reinforcing action of the weld bead. The internal crack was perpendicular to the surface (hereafter called a transverse crack), originated at the base-weld metal interface near the specimen midplane, and progressed toward the surface along this interface, except for the SW-101 ferritic stress relieved specimens of set 4, where, although having the same origin, it propagated into the weld metal. When the charge was insufficient to propagate the transverse crack to the surface, but more than enough to initiate it, another internal crack, similar to that in the prime plate tests, developed parallel to the surface in all but the SW-101 ferritic stress relieved specimens of set 4, in which the transverse crack propagated to the surface at a very small increase in charge. For specimens in sets 1 and 4 (SW-104 austenitic as welded, and SW-101 ferritic stress relieved) the surface crack appeared at the boundary of the weld, and usually in the weld metal itself for the others. The bulging of the specimens was limited, and complete failure occurred in all 3 and 5-inch specimens with no back spalling. The failure surfaces were primarily brittle in appearance. The weights of charge necessary for the appearance of the internal and surface cracks for the different sets of specimens were:

Set	Weld and Treatment	Specimen Width ¹	Weight of Charge (grams, ± 10)	
			Internal Crack	Surface Crack
1	Austenitic SW-164 as welded	3"	115	130
		5"	150	190
2	Ferritic SW-101 as welded	3"	110	115
		5"	130	140
3	Ferritic SW-101 armor treated	3"	95	105
		5"	115	135
4	Ferritic SW-101 stress relieved	3"	85	85
		5"	90	95

The subdivision method showed that the weld metal and heat affected zone in the as-welded ferritic SW-101 specimens, set 2, were generally under unequal biaxial tensions parallel² (longitudinal) and perpendicular (transverse²) to the weld when the average³ stresses across the thickness were considered, the stress values dropping rapidly in the base metal. The values of these stresses for the weld centerline and one inch away from the centerline, the latter being in the heat affected zone, are given below:

Specimen Width	Residual Stresses (psi)			
	Longitudinal		Transverse	
	At center-line	1 inch from centerline	At center-line	1 inch from centerline
3"	+ 2,500	0	+ 7,000	+ 7,000
5"	+16,000	- 1,000	+12,500	+10,000
11"	+35,000	+24,000	+13,500	+16,000

The residual stress measurements corresponding more nearly to the surface

1. The charges for the 11-inch wide specimens were the same as for the 5-inch width for set 1 and only slightly higher for sets 2, 3, and 4.
2. Note that here the terms parallel and transverse have different connotations than when used to describe crack orientation.
3. Strain gages mounted on full-thickness blocks cut from the specimens were considered to indicate the release of the average stresses; these blocks were then cut at their midplanes, and the final gage readings considered more nearly as indications of surface stresses.

stresses¹ differed appreciably from the average across the thickness, tabulated on the previous page, especially at the centerline, where biaxial compression was indicated, being greatest for the 3 inch-wide specimen. These changed to biaxial tension within 1/4 inch from the centerline in most cases.

Compared with those in the as-welded plate, the residual stresses remaining in the 11-inch stress-relieved plate were negligible.

3. Conclusions:

a) Prime Plate Tests:

The residual stress distribution induced by resistance heating had no effect on the behavior of the prime plate in the explosion tests, since it could have no effect on the formation of the initial internal crack parallel to the back face of the specimen. This crack occurred where the cohesive strength of the plate was first exceeded (and where it was a minimum) as the initial explosive compression wave in the plate was reflected as a tension wave from the back face. It is assumed that this wave traveled across the specimen under total lateral constraint, because of the inertia effect, leading to what, from the appearance of the surface, seemed to be a brittle fracture, although no direct proof of this exists.

Under these circumstances, the residual stress present could have no effect unless it had an appreciable component perpendicular to the crack, for the longitudinal and transverse components, even if they were large (which they were not, at the location of the crack within the plate), could not have added to or detracted from the very large (assumed) lateral constraint; and, even though the perpendicular component was a compression stress, its magnitude was only about 8,000 psi, so it could have had no effect.

1. See footnote 3, p. 18

The crack which propagated to the surface and appeared to be ductile in nature could not have been influenced by the surface residual stresses, for their values were very low in its vicinity. Further, the plastic flow would have removed any residual stresses originally present.

The occurrence of the internal and surface cracks could not have been influenced by the local softening which occurred during the heating to produce the residual stresses, for neither crack was in the softened area.

It may appear that the loss in strength exhibited by the stressed specimens (set 4) relative to the stress-relieved sets 2 and 3, might be attributed to the local softening, for the specimens softened throughout (set 5) were the weakest of all, but armor treated set 1 was harder than sets 2 and 3, yet also weaker. The conclusion reached is that the stress relief treatment resulted in "physical properties of the steel (which) give the best balance between the two conflicting characteristics, stress and strain, insofar as the surface crack is concerned. The observed decrease of the amount of charge in the stressed specimens may thus be explained as being produced by upsetting this balance in the softened area".

b) Welded Plate Tests:

In one-inch thick butt welded armor plate free from lateral constraint, the residual weld stresses have no effect on its performance in a high velocity explosion test. If a large reaction component of residual stress exists the results may be different.

As in the case of the prime plate specimens, the initial crack, although here transverse to rather than parallel to the surface, was produced under complete lateral constraint, and occurred where the cohesion strength for these specimens was lowest, at the weld-base metal junction. Also, as before, under such circumstances the residual stress system can only be effectual in influencing the initiation of such a crack if there is an appreciable component

perpendicular to the plane of the crack. The largest value of the average transverse residual stress determined at the crack location was 12,000 psi compression, and deemed probably insufficient to offset other factors, whereas the variation of this value with width of specimen was too small to affect the results as a function of width.

The variation of the residual stresses in the thickness direction was not investigated in detail, but the fact that the curves for so-called average and surface values of the transverse stress crossed at approximately the same distance from the weld centerline as the crack location, indicates that the transverse stress at the crack may not be larger than the average value across the thickness, and, hence, also have no effect on the initial crack.

There is little indication of the effect of the residual stress system on crack propagation. This follows from the observation that the difference in explosive charge required to form a surface crack relative to that for the internal crack is larger for the as-welded than for the stress-relieved specimens.

The austenitic welds were stronger than the ferritic welds under explosive loading, whereas the heat-treated ferritic welds were weakest of all, especially the stress-relieved set. The weld-base metal junction was the weakest spot for all sets of specimens.

The fact that a greater surplus of charge was required to propagate the internal crack to the surface in the prime plate specimens than in any welded specimen of corresponding width, bears out the observation found in the orientation tests on prime plate, that it is more difficult to propagate a parallel than a transverse crack.

C. OSRD Report No. 4396: Effect of Locked-Up Stresses on Ballistic Performance of Welded Armor - Part II

1. Experimental Program:

In a program like that reported for Part I, butt-welded armor plate specimens, prepared with various electrodes and subjected to differing heat treatments, were subjected to explosive loading, and their resistance to fracture and the nature of the fracture investigated. Residual weld-stress systems were investigated with particular attention being paid to the variation of stress in the thickness direction.

Five sets of 12-inch by 12-inch by 1-inch thick armor plate specimens with a double-V butt weld running down the center, were prepared as follows:

<u>Set</u>	<u>Weld</u>	<u>Treatment</u>
1	Austenitic	As welded
2	Austenitic	Stress relieved
3	Austenitic	Armor treated
4	Ferritic NRC-2A	As welded
5	Ferritic NRC-2A	Stress relieved

The original plates for sets 1 and 4 were stress-relieved before welding. Each set included at least six specimens.

Explosion tests were run as in Part I, with charge values for the internal and surface crack appearances noted. In addition, the three-dimensional residual stress patterns were determined using the Norton and Rosenthal technique for as-welded sets 1 and 4, and for stress-relieved set 5. As before, a section perpendicular to the weld in the middle portion of the plate was analysed. The 11-inch wide ferritic SW-101 as-welded plate, partially analysed for residual stresses in Part I, was considered further here to determine the distribution across the thickness. Finally, a few stress determinations were made on a 25-inch long ferritic NRC-2A as-welded plate to obtain some idea of the maximum value of residual stress which can be expected in actual weldments.

Table III - Test Plate DataAnalysis (of 1-inch thick prime plate):

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Mo</u>
0.26	1.65	0.016	0.018	0.19	0.48

(Note: no analysis given for 4-inch thick prime plate used in crack orientation tests.)

Electrodes: NRC-2A Ferritic

Austenitic (no further designation given but no doubt is SW-164 electrode used in Part I, as data from the latter are included for comparison.)

Welding Preheat: none

Interpass Temperature: 100° - 320°F for ferritic welds

100° - 330°F for austenitic welds

Heat Treatments:

Armor heat treatment: 1-1/2 hours at 1625°F, spray quench and draw at 860°F for 3 hours, air-cooled, BHN 352-363.

Stress relief heat treatment: 1/2 hour at 1135°F, air-cooled, BHN 275

Yield Point of Prime Plate: "believed to be" about 100,000 psi.

2. Results:

The behavior of the weldments under explosive loading was somewhat similar to that found in Part I. Surface indentation and a small amount of bending in the weld were observed. The internal crack for the austenitic welds (sets 1, 2, and 3) was transverse and originated in the weld metal-base-metal junction. At larger charges a parallel crack appeared in the bottom half of the specimen and joined the transverse crack, the transverse

crack then propagating to the surface mostly at the boundary of the weld. In the ferritic NRC-2a welds (sets 4 and 5), however, the crack originated within the weld metal; a transverse crack appeared in the bottom half of the specimen for the as-welded plates (set 4), while a more nearly parallel crack originated in the weld at the midplane for stress-relieved set 5, propagating transversely with larger charges. Failure in these specimens progressed with the appearance in the bottom half of the weld of parallel cracks which joined the transverse cracks before the latter appeared at the surface in the weld metal. Charges sufficiently large for bulging, back spall, and complete failure were not used.

The approximate weights of charge necessary for the appearance of the internal and surface cracks for the different sets of specimens are tabulated below. Figures for the 11-inch ferritic welds made in Part I are included for comparison.

Set	Weld and Heat Treatment	Weight of Charge (grams)	
		Internal Crack	Surface Crack
1	Austenitic as welded	130 \pm 20	200 \pm 10
2	" stress relieved	80 \pm 20	150 \pm 5
3	" armor treated	80 \pm 20	130 \pm 5
4	Ferritic NRC-2A as welded	105 \pm 10	190 \pm 10
5	" " stress relieved	120 \pm 10	200 \pm 5

From Part I:

2	Ferritic SW-101 as welded	135 \pm 10	150 \pm 10
4	" " stress relieved	105 \pm 10	110 \pm 10
3	" " armor treated	125 \pm 10	145 \pm 10

As in Part I, the measurements of the average¹ residual stress through the thickness of the plate for various distances from the weld center line

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1. True, averages, taking into account the detailed variation through the thickness, and not, as in Part I, the averages indicated by surface gages when full thickness blocks were cut out. That there is a difference may be seen by comparing the figures for the SW-101 weld with those given for this weld in Part I; it will be noted that the change is greatest for the transverse stress.

showed that unequal longitudinal and transverse tension existed at the weld, with the following values for the centerline and one inch from it in the heat-affected zone:

Specimen	Residual Stress (psi)			
	Longitudinal		Transverse	
	At center-line	1-inch from centerline	At center-line	1-inch from centerline
Austenitic as welded	+ 61,000	+ 8,000	+ 2,500	+ 8,000
Ferritic NRC-2A as weld.	+ 55,000	+ 26,000	+ 11,000	+ 5,00
Ferritic SW-101 as weld.	+ 43,000	+ 26,000	+ 6,000	+ 9,000

Since the yield point of the armor plate is around 100,000 psi, it is plain that the above average stresses do not approach it.

The measurement of the variation of residual stresses through the thickness of the weldments revealed that this variation was considerable for both the longitudinal and transverse components. In the case of the longitudinal stress there is a relatively small tension on both faces with a tension peak in the interior toward the bottom half of the weld. For the transverse stress the small average values tabulated above are the results of zones of high tension near the faces and high compression near the mid-thickness. The values are tabulated below:

Specimen	Residual Stress (psi)							
	Longitudinal				Transverse			
	At Centerline		At weld-base metal junction		At Centerline		At weld-base metal junction	
	Surface	Interior	Surface	Interior	Near Surface	Mid-Thickness	Near Surface	Mid-Thickness
Austenitic as-welded	+29,000	+77,000	+14,000	+52,000	+38,000	-48,000	+28,000	-29,000
Ferritic NRC-2A as-welded	+23,000	+86,000	+35,000	+76,000	+60,000	-58,000	+30,000	-29,000
Ferritic SW-101 as-welded	+18,000	+ 76,000	+16,000	+52,000	+49,000	-31,000	+22,000	-22,000
25-inch Ferritic SW-101 as welded	+14,000	+99,000	+28,000	+84,000	+15,000	-108,000	+13,000	-59,000

The stress at the weld centerline in the thickness direction was a tension stress for the first three specimens tabulated above, with peaks near the mid-thickness of +2,500, +8,000, and +5,500 psi, respectively. Thus, these are negligible, especially in view of the accuracy of measurement of ± 4000 psi.

The residual stresses in the stress relieved NRC-2A weldment were negligible.

3. Conclusions:

The residual weld stresses have but a minor influence on the performance of one-inch thick butt-welded armor plates free from lateral restraint in a high velocity explosion test. Their possible slight influence on internal crack initiation has not been proved, and they do not influence the crack propagation.

Since, because of the assumption of lateral constraint, made as in Part I, only an appreciable stress component perpendicular to the direction of the initial transverse crack could influence crack formation, only the transverse stresses need be considered. From their values through the thickness it is seen that the deleterious effect of heat treatment on the explosive test performance of the austenitic and ferritic SW-101 welds might be explained by the removal of the 29,000 psi compression peaks at mid-thickness of the weld-base metal junction, while the corresponding beneficial effect of heat treatment for the ferritic NRC-2A weld might be due to the removal of the 60,000 psi tension peak near the surface at the centerline, these being the respective locations of the initial cracks in these weldments. This seems to be born out for the NRC-2A weld by the change in orientation of the initial crack through the heat treatment from transverse to parallel.

It is felt this benefit of heat treatment for the NRC-2A weld, the only one shown in any of the tests, including Part I, shows what at best can be expected of the effect of heat treatment on residual weld stresses in one-inch armor, but that the deleterious effect of heat treatment on the other welds is too large to be accounted for by stress changes. When the added fact of a decreased surplus

charge for crack propagation (an indication of increased notch sensitivity) is considered, metallurgical changes, possibly carbide precipitation at the weld-base metal interface, are suspected. In any case, heat treatment of welded armor plate may well do more harm than good.

Because the failure cracks began in the weld metal rather than at the weld-base metal junction, the ferritic NRC-2A welds have a relatively stronger bond and better homogeneity of joint than the austenitic or ferritic SW-101. Thus the nature of the welded joint offers the true explanation of the explosion test results.

The investigation of the residual stresses as a function of thickness reveals a nearly biaxial system varying considerably with distance from the surface. A knowledge of this variation has been of more value than the average stresses in interpreting the role of residual stress on performance for these weldments. The residual stress patterns obtained with the different types of electrode are similar in most details and all show stress peaks of about the same magnitude.

IV. Discussion and Evaluation of Reports

A. OSRD Report No. 3348: A Preliminary Investigation of Residual Stresses in a Welded H-Plate.

Although investigations such as this devoted exclusively to the measurement of resultant residual weld stresses do not by themselves help to answer any of the pressing questions of the effect of such stresses on weldability, they are nevertheless worthy contributions to the literature. As more knowledge becomes available on the effect of residual stresses on weldment performance, certain general principles will become apparent. Once this stage of the science is reached, data on the nature and magnitudes of the weld stresses which are present will no doubt help considerably to predict performance, at least as far as performance is so affected. In other words, the accumulation of such data is part of the progress toward rationality in the weld stress problem.

The welding engineer is also much concerned with the effect of the many welding variables on the resultant stresses in a weldment. This can only be investigated by the direct measurement and correlation of such stresses with the welding procedure used.

The report being discussed contributes, although only to a limited extent, to welding knowledge in the above fields, and is thus of some interest to the present welding engineer. An admittedly preliminary survey is made of the residual weld stresses in an H-plate and the fact is noted that an "armor" heat treatment reduces certain of these stresses to some degree. The value of the report will be enhanced when more understanding is achieved of the effect of such residual stresses on performance. In view of the present lack of such understanding, the implication, made at one point, that the data may aid in the interpretation of ballistic test results on armor plate (presumably

in the form of H-plates), seems somewhat premature. Quoting no less of an authority than Spraragen in a very recent publication (1a), he "does not recall a single instance in which laboratory tests of structural steels have demonstrated beyond a shadow of a doubt that there is any significant difference in behavior of a structure or specimen with residual stresses and one without residual stresses." His later comments in the same article show that this remark refers to structures explosively loaded as well as to static loading tests and impact tests at ordinary loading rates. At the time of the H-plate tests under consideration, the reports, discussed below in parts (B) and (C) of this section, on ballistic-type testing of armor plate had not yet appeared, and Miklowitz (1a) finds these the only published results of their nature available even now. Thus no known correlation between residual weld stresses and performance could have been made at the time, nor, for that matter, has such yet been made with any certainty for any conditions of test. It is not meant here to belabor this point unduly, but merely to emphasize it, because it is not widely appreciated, and because it bears so directly on the tests described in the later sections of this report.

Insofar as it was possible to accomplish the stated objective of ascertaining the order of magnitude of the residual weld stress pattern in a welded H-plate using only one undamaged test plate, this was done, with considerable care and ingenuity being exercised in its achievement. As is pointed out by the authors, a different sequence of sectioning the H-plate might have resulted in somewhat different stress values for some locations, but one can only agree with their opinion that the differences would probably not be great. The method and sequence they suggest in the light of their experience seem as much aimed at systematization and convenience as at increased accuracy.

The fact is established that residual stresses exist in the H-plate of the order of magnitude of the proportional limit of the base plate. Thus it would seem that an H-plate¹ provides one of the most important conditions for the weldability test it is intended to be (at least as far as requirements for this type of test are understood), namely, sufficient constraint that so-called "yield point", or, more accurately, proportional limit, stresses are set up. A closer inspection of the data, however, raises a question in this regard. The measured stresses which approached the proportional limit were located in a leg of the H and not in the cross-bar. The welding sequence used for such a plate specifies that the legs be welded first, thus providing the constraints which, it is expected, will cause high residual stresses in and near the cross-bar when the latter weld is completed, this being the final step in the sequence. The tests showed, however, that the maximum residual stresses in and near the cross-bar weld were considerably lower than those in one leg. The significance of this seemingly unexpected result is not clear, for the effect of such residual stresses on performance is unknown, as stated above, and if the only constraint requirement for H-plates, etc., is that a proportional limit stress exist somewhere in the weldment, then it has little if any significance.

The (essentially) static bending tests on the as-welded and "armor" heat-treated H-plates show that the residual weld stresses are reduced by the armor heat treatment. The full amount of the reduction may not have been shown, however, even for those particular gage locations used, because the maximum load was insufficient to cause yielding. It can only be said that

1. Or at least the H-plate tested.

at the particular gage subjected to the maximum stress by the bending load, the residual stress had been reduced to less than 30,000 psi, to less than approximately 50,000 psi at the gage subjected to the minimum stress, and to intermediate values at the few other locations considered.

The relief of stress by the armor heat treatment is not surprising, as the final step (normalizing by holding at 1230°F for 3 hours, then air cooling) is not far removed in its macroscopic aspects from an ordinary stress relieving treatment, since at that temperature and time at temperature stress relief would certainly occur, and there is no reason that air cooling, provided it is relatively uniform over the surface, would induce further macroscopic residual stresses.

It is unfortunate that H-plate NR-17, which had been ballistically fractured before being examined for residual stresses, had not originally been of the same composition and welded in the same way¹ as plate NR-27, for then a better indication of the effect of the ballistic test on the residual stresses would have resulted.

In summary, then, it may be stated that OSRD Report No. 3348 constitutes an interesting and valuable exploratory contribution to residual weld stress literature. It proves that residual stresses of the order of magnitude of the proportional limit of the prime plate exist in an as-welded armor steel H-plate, and that these are considerably reduced by subjecting the plate to (1) plastic deformation and (2) an armor heat treatment. The full value and practical application of these results, however, must await a future thorough understanding of the effect of residual weld stresses on weldment performance.

1. It had a single-V weld throughout, as opposed to the double-V weld used on plate NR-27.

B. OSRD Report No. 3580: Effect of Locked-Up Stresses on Ballistic Performance of Welded Armor - Part I

It would be extremely desirable to be able to state that the above report contains conclusive evidence of the effect of residual weld stresses on the ballistic performance of welded armor. Unfortunately, however, this does not seem to be the case. The authors of the report felt that the experimental evidence permitted them to draw the conclusion that no effect of the residual stresses was detected under the conditions investigated. However, as pointed out in the introduction to the present report (Section II), the whole question of the effect of residual stresses on weldment performance is intimately related to the problem of the fracturing of metals, and involves all the complexities of this problem, especially those connected with the initiation and propagation of cracks.¹ Although the authors based their explanation of the results on what seem at first to be reasonable assumptions, it is felt here that the experimental approach used in the investigation was not sufficiently fundamental to the fracture problem to permit a truly proper evaluation of the results at the present stage of knowledge in this field. Thus, in this respect,² a final judgement of the ultimate value of the report must be held in abeyance, pending a fuller understanding of fracture phenomena. However, it is equally true² that valuable and immediately practical, although not particularly fundamental, information is presented in the report in regard to the effect of the type of weld and its subsequent heat treatment on the very

1. Reference to the recent and extremely pertinent survey volume edited by Osgood (1a) is highly recommended for the light it will throw on the "present state of the art" in the field of residual stresses, the nature of, and lack of information on, the fracture problem, and the relation of the two.

2. as in Part A, above.

high-speed impact behavior of double-V butt welds in armor plate.

To be specific, and referring to the residual stress results, the conclusion that those stresses reported to exist in the welds which were tested did not affect the performance at very high loading rates was based primarily on the following assumptions: only an appreciable tensile component of stress perpendicular to the cracks which formed could influence their formation; the fracture occurred where the "cohesive" strength of the plates was lowest; fracture was initiated by the explosion-induced tension wave which was reflected from the "back" of the specimen; and, this tension wave traveled across the specimen under "total lateral constraint," this constraint being sufficiently great to obviate any effects of the transverse and longitudinal stress components. Although a logical argument seems to be built on these assumptions, reference to Kolsky's recent monograph on stress waves in solid media (15), the work of Rinehart and co-workers on the effects of explosive loading on metals (16) and the many discussions of the fundamentals of the fracture problem (1a,14), suggests that, at the least, these assumptions are open to serious question, and that ultimate answers are only to be found by a basic approach on the microscopic as well as the macroscopic front, and beginning with the most elementary cases. Further, these should probably be started with small-scale "laboratory-type" tests [as strongly urged by Miklowitz (1a) and, separately, by Osgood (1a)] ; static tests should precede even low-speed dynamic tests, and very high-speed impact tests (explosive loading) with their enormously-increased complexity of interpretation, run only when the phenomenon is fully understood for the other speed ranges.

Before any such real understanding of the effect of residual weld stresses on the performance of weldments under explosive loading can be achieved, answers must be found, for example, to questions such as the following: with

due regard to the realities of the microstructure, what are the conditions of stress at a point in a metal which give rise to a crack?¹; how are these conditions affected by strain rate, temperature, and prior thermal and deformation history?; what changes in these conditions, if any, are necessary for the propagation of a crack (i.e. what is the "latent energy" of crack propagation)?; "in what specific cases and to what degree, if any, (do) residual stresses and load stresses superpose under high rates of loading?"²; what, if it exists for the metal under consideration, is the effect on fracture of a delay time for the initiation of plastic deformation?; "how do the detailed weldment geometry³ and microstructure affect the transmission, reflection, and focusing, etc., of explosive-induced stress waves?; of what significance to fracture is the fact that "the velocity of crack propagation is generally lower than the velocity of stress propagation" for high-speed impact loading?; and others equally difficult to answer experimentally. Thus, it can be seen that the problem is a highly complex one, and only by maintaining strict control of all parameters but one and varying the latter in a known way, will significant results be obtained.

The authors of OSRD 3580 could reach no conclusions regarding the effect of residual stresses on the propagation to the surface of the internal parallel and transverse cracks which formed in the prime-plate and as-weld specimens, respectively, for the accompanying plastic deformation obliterated whatever such stresses had existed. This emphasizes the importance of attempting to

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1. Campus (1a) states, "it is questionable whether the cracks have to be initiated or whether their beginnings already exist." (This is not a reference to dislocations, but to "effective defects on a larger scale.")
 2. Miklowitz (1a)
 3. It will be recalled that in the tests described in OSRD 3580, the weld beads were not removed by grinding, whereas the prime plate tests, of course, had no such beads.

eliminate, insofar as this is possible, at least gross plastic deformation from specimens being used in studies of the effect of residual stresses on performance.

Of interest to the welding engineer is the unequivocal evidence found that the welds made with austenitic SW-164 electrodes were stronger ballistically than those made with ferritic SW-101 electrodes, although admittedly any other result would have been surprising. It was also shown that both the armor and stress relief heat treatments reduced the strength under explosive loading of the plates welded with ferritic electrodes; heat treatment after welding can thus be more detrimental than beneficial under certain circumstances, a fact of much practical importance, for the tendency is often to post-weld heat treat merely "on general principles."

The weld stress investigation was limited by the lack of information about the variation of the residual weld stresses across the plate thickness, emphasizing the need for such data in any thick plate residual stress research. The realization of this led, in part, to the work reported in OSRD 4396.

C. OSRD Report No. 4396: Effect of Locked-Up Stresses on Ballistic Performance of Welded Armor - Part II.

Although some slight evidence of the effect of residual weld stresses on ballistic performance is claimed in this report, the arguments presented in Part B, above, apply here as well. It can only be said that such an effect may exist, and that it has not been shown to be absent; until a more fundamental approach to the problem is made, such evidence must be treated as inconclusive, at best. In addition, as the authors admit, there is no convincing evidence that the effects observed were not entirely the result of metallurgical and structural changes, in spite of the change in crack orientation which is offered as an important confirming piece of evidence.

It is appropriate to point out here that all existing three-dimensional residual stress measurement techniques are not only complex and tedious in application, but, being indirect, can only be approximate and subject to considerable errors. The tolerances stated in the reports, large as they are, may, in fact, be too small. The following comment by Osgood (1a) is extremely pertinent and must be seriously considered if progress is to be made in residual weld stress research: "It is imperative that better and simpler non-destructive methods of measuring residual stresses over small areas be developed, and these methods should not be limited to the measurement of surface stresses. The measurement of any property of a metal which depends on the state of stress should be considered as a potential basis for a method by which residual stresses could be determined."

On the evidence of the appearance of the first internal crack, the ferritic SW-101 welds may have been¹ stronger than the unheat treated austenitic

1. The test-result tolerances overlap the compared values, so the evidence might not be confirmed if more tests were run.

welds. In the heat-treated condition the evidence for this appears to be more convincing. This rather unexpected result is the principal supporting evidence used by the authors for their claim of an observed residual stress effect, but the many uncontrolled variables in the tests could well be the basis for a different interpretation.

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